Second Generation High Temperature Superconducting Wire: Fabrication, Properties, and Potential Applications

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SR 2008, June 2008, Novosibirsk, Russia
Acknowledgements

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- National High Magnetic Field Laboratory at Florida State University
- Fermi National Accelerator Laboratory
- Oak Ridge National Laboratory
Superconductivity 101

What is a Superconductor?

An element, inter-metallic alloy, or compound that will conduct electricity without resistance below a certain temperature. Resistance is undesirable because it produces losses in the energy flowing through the material.

Superconductors exist in a region bounded by:

- Temperature (Tc)
- Magnetic Field (Hc)
- Current Density (Jc)
Two general classes of superconductors have been commercialized

“Low temperature” superconductors
  – Operation limited to low temperatures near 4 K (LHe)
  – First commercial superconductors
  – NbTi, Nb3Sn

“High temperature” superconductors
  – Operation from 4 K (LHe) to 77 K (LN2)
  – 1G: BSCCO-based
  – 2G: YBCO-based
  – 2G: thin film vs. wire drawing processing
  – Moving from development into commercialization

NbTi and Nb3Sn Superconductors (Luvata)
1G BSCCO-2223 Tape (AMSC)
2G YBCO Wire (SuperPower, Inc.)
Superconductivity is an enabling technology to move high energy density power.

- Current carrying capability of copper ~ 200 A/cm²
- Current carrying capability of 2G superconductor film ~ 5,000,000 A/cm² ($J_c$)
- Current carrying capability of 2G superconductor wire ~ 50,000 A/cm² ($J_e$)
Structure and Main Processing Steps

1. Electropolishing
2. Pilot IBAD
3. Pilot Buffer

- 20µm Cu
- Hastelloy substrate
- MOCVD
- HTS
- LMO
- Homo-epi MgO
- IBAD MgO
- Copper Plate
SuperPower is unique in the world in having established operational 2G Pilot Manufacturing facilities.
Remarkable progress in 2G wire scale-up over the last 5 years

Critical Current * Length (A-m)

1 m to 935 m in 5 years
Also, Ic doubled & speed increased 12-fold to 180 m/h*

*4 mm speed equivalent

Synchrotron Radiation 2008, Novosibirsk, Russia, June 2008
Long length processing of 2G HTS wire demonstrated

- Minimum $I_c = 170$ A/cm over 935 m
- $I_c \times$ Length = 158,950 A-m
- Uniformity over 935 m = 10.6%

**Graph:**

- Critical current (A/cm) vs. Position (m)
- 77 K, $I_c$ measured every 5 m using continuous dc currents over entire tape width of 12 mm (not slit)

<table>
<thead>
<tr>
<th>Process</th>
<th>Speed of 4 mm tape (m/h)</th>
</tr>
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<tbody>
<tr>
<td>IBAD MgO</td>
<td>360</td>
</tr>
<tr>
<td>Homo-epi MgO</td>
<td>345</td>
</tr>
<tr>
<td>LMO</td>
<td>345</td>
</tr>
<tr>
<td>MOCVD</td>
<td>135</td>
</tr>
</tbody>
</table>

Synchrotron Radiation 2008, Novosibirsk, Russia, June 2008
 Capability of ~ 1000 A in 12 mm widths achieved!

- 3.5 µm film made in 10 passes: $I_c = 964$ A = 803 A/cm ($J_c = 2.06$ MA/cm$^2$)
- 2.1 µm film made in 6 passes: $I_c = 929$ A = 774 A/cm ($J_c = 3.68$ MA/cm$^2$)

Over 1.2 m length, $I_c = 964$ A = 803 A/cm

Ic measurement using continuous dc current (no pulsed current) across entire tape width of 12 mm No patterning
HTS application for “big science” - from SR to high energy physics

- LN$_2$ magnets
- High field LHe magnets
- Current limiters
- Currents leads
- Cables with high current density
High Field Coil Demonstrated – 2.4T at 64K

1.1 T Coil at 77 K!

2.4 T at 64 K
Collaboration with FermiLab (4mm wide, SCS)
FermiLab’s comparison of different wire types

HTS and LTS Performance at 4.2 K
2G YBCO HTS offers distinct advantages in high magnetic field current density over “traditional” LTS wire.
Dramatic improvements achieved in in-field performance of our 2G wire

For 0.7micron recipe-2*
Recipe-1: strong pinning for B//ab
Recipe-2*: strong pinning for B//c

Best in-field performance in commercial 2G wires

For 3.3micron film of recipe-2*
Ic_minimum(77K, 1T) = 185.6A/cm
Ic_minimum(65K, 3T) = 267.3A/cm
Ic(77K, B//c=3T) = 71.8A/cm

Synchrotron Radiation 2008, Novosibirsk, Russia, June 2008
Data from Y. Zhang, M. Paranthaman, A. Goyal, ORNL
Mechanical properties of 2G wire are ideal for high field, high stress applications

<table>
<thead>
<tr>
<th>Conductor</th>
<th>$I_c / I_c_{\varepsilon=0}$</th>
</tr>
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<tbody>
<tr>
<td>SP 2G</td>
<td>&gt; 0.95 for $\varepsilon \sim 0.35%$</td>
</tr>
<tr>
<td>1G high strength</td>
<td>&gt; 0.95 for $\varepsilon \sim 0.40%$</td>
</tr>
<tr>
<td>1G low strength</td>
<td>&gt; 0.95 for $\varepsilon \sim 0.45%$</td>
</tr>
<tr>
<td>Nb$_3$Sn, 4 T</td>
<td>&lt; 0.90 @ 0.4%</td>
</tr>
<tr>
<td>Nb$_3$Sn, 8 T</td>
<td>&lt; 0.82 @ 0.4%</td>
</tr>
<tr>
<td>Nb$_3$Sn, 12 T</td>
<td>&lt; 0.68 @ 0.4%</td>
</tr>
<tr>
<td>Nb$_3$Sn, 16 T</td>
<td>&lt; 0.35 @ 0.4%</td>
</tr>
</tbody>
</table>

Comparative Operating Stress-Strain Operating Windows for High Field Superconductors
NHMFL facilities provide 19T axial background field

Insert coil tested in NHMFL’s unique, 19-tesla, 20-centimeter wide-bore, 20-megawatt Bitter magnet

2G HF Insert Coil Showing Terminals, Overbanding and Partial Support Structure. Flange OD is 127 mm.
2G high field insert coil demonstration

Wire Specifications:

Dimensions: 4 mm wide x 95 microns thick
Substrate: 50 micron Hastelloy
HTS: ~ 1 micron YBCO
Stabilizer: ~ 2 micron Ag on YBCO
~ 20 microns of surround copper stabilizer per side
Tape Ic 72 – 82 A, 77 K, sf

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Coil ID</td>
<td>9.5 mm (clear)</td>
</tr>
<tr>
<td>Winding ID</td>
<td>19.1 mm</td>
</tr>
<tr>
<td>Winding OD</td>
<td>~ 87 mm</td>
</tr>
<tr>
<td>Coil Height</td>
<td>~ 51.6 mm</td>
</tr>
<tr>
<td># of Pancakes</td>
<td>12 (6 x double)</td>
</tr>
<tr>
<td>2G tape used</td>
<td>~ 462 m</td>
</tr>
<tr>
<td># of turns</td>
<td>~ 2772</td>
</tr>
<tr>
<td>Coil Je</td>
<td>~1.569 A/mm² per A</td>
</tr>
<tr>
<td>Coil constant</td>
<td>~ 44.4 mT/A</td>
</tr>
</tbody>
</table>

Coil Winding:

Double Pancake Construction
Dry Wound (no epoxy)
Kapton polyimide insulation (co-wound)
Overbanding: 316 Stainless Steel
High field insert coil achieves world records for highest HTS field, highest magnetic field by a SC magnet

Peak hoop stress ~ 215 MPa, well below tape limit

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<tbody>
<tr>
<td><strong>Ic of Tapes in Coil</strong></td>
<td>72 A – 82 A (77K, sf)</td>
</tr>
<tr>
<td>4.2 K Coil Ic - self field</td>
<td>221 A</td>
</tr>
<tr>
<td>4.2 K Amp Turns @ Ic - self field</td>
<td>612,612</td>
</tr>
<tr>
<td>4.2 K Je @ Ic, self field</td>
<td>346.7 A/mm²</td>
</tr>
<tr>
<td>4.2K Peak Radial Field @ Ic, self field</td>
<td>3.2 T</td>
</tr>
<tr>
<td>4.2 K Central field – self field</td>
<td>9.81 T</td>
</tr>
<tr>
<td>4.2 K Coil Ic – 19 T background (axial)</td>
<td>175 A</td>
</tr>
<tr>
<td>4.2 K Amp Turns @ Ic – 19 T background (axial)</td>
<td>485,100</td>
</tr>
<tr>
<td>4.2 K Je @ Ic, 19 T background (axial)</td>
<td>274.6 A/mm²</td>
</tr>
<tr>
<td>4.2 K Peak Radial Field @ Ic, 19 T bkgd (axial)</td>
<td>2.7 T</td>
</tr>
<tr>
<td>4.2K Central Field – 19 T background (axial)</td>
<td>26.8 T</td>
</tr>
</tbody>
</table>
Thin-profile wire (50 micron substrate) exhibits superior bend properties in joints & splices

- 4 mm wide conductors each with 20 µm surround copper stabilizer
- Joint or splice length = 3 or 3.5 cm
- Original tape thickness = 0.095 mm
- Thickness at joint or splice = 0.22 mm (~2 times thinner than with 1G or other 2G!)

No degradation in $I_c$ (1 $\mu$V/cm) over the joint or splice
Joint or splice resistivity = 40 to 50 n$\Omega$cm$^2$

No degradation in $I_c$ and resistivity when joint or splice is bent over down to 1” diameter and thermal cycled three times. $I_c$ was tested at every thermal cycle
Current Leads Comparison

Baseline:
- Current: 100 A
- Temperature: 77 K to 4.2 K

<table>
<thead>
<tr>
<th>Type</th>
<th>Heat Leak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized non-SC lead, non-vapor cooled:</td>
<td>1.2       W</td>
</tr>
<tr>
<td>Optimized non-SC lead, vapor cooled:</td>
<td>0.092     W</td>
</tr>
<tr>
<td>1G alloyed Ag HTS lead (^{(1)}), non-vapor cooled, 0.25 m long:</td>
<td>0.018 W</td>
</tr>
<tr>
<td>2G Ag HTS lead (^{(2)}), non-vapor cooled, 0.25 m long:</td>
<td>0.013 W</td>
</tr>
<tr>
<td>2G alloyed Ag HTS lead (^{(3)}), non-vapor cooled, 0.25 m long:</td>
<td>0.0008 W</td>
</tr>
</tbody>
</table>

- All values assume top end anchored at 77K
- Vapor cooling of HTS leads will reduce the heat leak significantly below the values stated
- Heat leak with HTS leads scales as 1/Length

\(^{(1)}\) 1G tape, 4.2 mm x 0.22 mm, 65% Ag-4 wt% Au

\(^{(2)}\) 2G tape, 4 mm x 0.053 mm, 50 µm Hastelloy® C276 substrate with 2 µm thick Ag cap layer (no Cu)

\(^{(3)}\) 2G tape, 4 mm x 0.053 mm, 50 µm Hastelloy® C276 substrate with 2 µm thick Ag-4 wt% Au cap layer, (no Cu)
2G Wire for SFCL shows consistent, excellent performance

- High-power SFCL test: 2G
- Prospective current: 90 kA*
- Limited current: 32 kA
- Peak current through element: 3 kA
- Response time: < 1 ms
- Element quality range: Narrow

Fast response time

Quench speed around 0.5 ms

Response time: 3 kA
Peak current through element: 90 kA*
Limited current: 32 kA
Prospective current: 32 kA
Element quality range: Narrow
Structure and Properties of Albany BSCCO Cable

3-in-One Cable Design
- Compact size (O.D. = 135mm) (5.3”)

HTS Conductor and Shield Winding
- Di-BSSCO wire (Long length, High-Ic, High-strength, anti-ballooning)
- Equal current distribution to minimize AC loss
- Cancel magnetic field → EMI free

Electrical Insulation
- PPLP with high dielectric strength & small tangent loss

Fault Current Protection
- Cu former and shield windings to handle 2nd contingency fault conditions

Thermal Contraction
- 3-cores are loosely stranded to accommodate 0.3% contraction

Thermal Insulation
- Stainless steel cryostat for low heat inleakage

[Shipping Test Results]
- Critical Current
  1.8 kA (at 77K, DC) → same as design
- Voltage Test (based on AEIC)
  AC: 69kV · 10min (no PD)
  Imp: +/- 200kV, 10 shots/each
- AC loss
  0.7W/m/ph (at 0.8kA) → same as design
- Cable Bending Test (18; 1.2mR)
  No Ic degradation
  No defect in HTS wires and electrical insulations
Summary

We have not reached the limit of 2G HTS wire capability, but our HTS wires are ready NOW for a number of magnetic and other high tech applications.
Questions?

Thank you for your interest!

For further information about SuperPower, please visit us at:  www.superpower-inc.com

or e-mail:  info@superpower-inc.com